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THE MEASUREMENT OF NUCLEAR HEATING IN MATERIALS BY USE OF A ROD CALORIMETER

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THE MEASUREMENT OF NUCLEAR HEATING IN MATERIALS BY USE OF A ROD CALORIMETER

1.0 Introduction

The measurementof the absorbed energy for samples of materials in particular nuclear radiation environments is a simple and straightforward process. However, the design of the calorimeter is subject to the physical properties of the material being investigated and the magnitude of the absorbed energy rate, and these factors must be properly applied in the design of the calorimeters for accuracy in the measurement.

Simple adiabatic calorimeters can be employed, but these are limited in accuracy to a very narrow range of radiation intensity and even then, operable for only a short time period.

A rod calorimeter is a rate reading device which can be designed for accurate measurement of absorbed energy over perhaps two decades of radiation intensity. A brief description of these calorimeters follows and a design example is given.

2.0 The Rod Calorimeter

The principle of the rod type calorimeter is that the heat energy absorbed in the rod must be conducted down the rod to a heat sink. The temperature gradient along a uniform cross sectional area rod and the thermal conductivity of the rod are sufficient to determine the conductive heat transfer. In the steady state condition, the energy loss is equal to the energy absorbed by the rod from the radiation field. Other heat losses due to convection, conduction, or radiation must be minimal compared to the heat conduction through the rod.

Consider a rod, one end of which is attached to a heat sink and the other end free. Assume the material is absorbing energy at the rate $d\dot{q}$ per incremental volume and the rod has a constant cross sectional area A. At a position x along the rod, the incoming heat rate is

$$\dot{q}_1 = -kA\frac{dT}{dx} \quad \text{cal sec}^{-1} \tag{1}$$

where k is the thermal conductivity of the material. At a position x + dx closer to the heat sink, the heat transfer will be

$$\dot{q}_2 = -kA\left(\frac{dT}{dx} + \frac{d^2T}{dx^2}dx\right) \quad \text{cal sec}^{-1} \tag{2}$$

The heat originating in the volume A dx is

$$d\dot{q}_3 = d\dot{q}\,A\,dx = \dot{q}_2 - \dot{q}_1 \quad \text{cal sec}^{-1} \tag{3}$$

Combining these equations, we obtain

$$\frac{d^2T}{dx^2} = \frac{-d\dot{q}}{k} \tag{4}$$

This is easily integrated to obtain

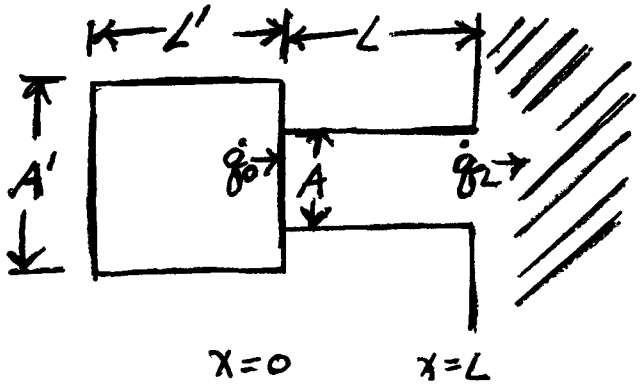
$$\frac{dT}{dx} = \frac{-d\dot{q}}{k}x + M \tag{5}$$

$$T = \frac{-d\dot{q}\,x^2}{2k} + Mx + N \tag{6}$$

The constants T, M and N may be deduced from the boundary conditions of a particular calorimeter design. We will examine in detail one such design.and demonstrate the performance characteristics and limitations.

3.0 A Specific Design.

Consider the design of a calorimeter to measure the absorbed energy in aluminum in a radiation field of approximately 10^8 r/hr. The rod may have any of many shapes and dimensions, but consider an axially symmetrical rod as below.



The boundary conditions for equation 6 are $T = T_1$ for $x = o$ and $T = T_2$ for $x = L$, and we have

$$N = T_1$$

$$M = \frac{T_2 - T_1}{L} + \frac{\dot{d}qL}{2k} = \left(\frac{dT}{dx}\right)_{x=o} \tag{7}$$

and equation 6 may be written as

$$T = T_1 - \left(\frac{T_1 - T_2}{L}\right) x + \frac{\dot{d}q\, x}{2k} (L - x) \tag{8}$$

Now
$$\dot{q}_o = -k A \left(\frac{dT}{dx}\right)_{x=o} = -k A M \tag{9}$$

$$\dot{q}_o = -k A \left[\frac{T_2 - T_1}{L} + \frac{\dot{d}q L}{2k}\right] \tag{10}$$

or
$$\dot{q}_o + \frac{\dot{d}q AL}{2} = \frac{k A}{L} (T_1 - T_2) \tag{11}$$

In the above equation $\dot{q}_o$ is simply the heat absorbed in the large portion of rod, therefore

$$\dot{q}_o = \dot{d}q\, A' L' \tag{12}$$

and substitution of this expression into equation (11) yields

$$d\dot{q} = \frac{2k\,A\,(T_1 - T_2)}{L\,(2A^1L^1 + AL)}\ \text{cal cm}^{-3}\text{sec}^{-1} \qquad (13)$$

A thermocouple may be placed at the positions to measure T_1 and T_2, and all the other factors can be accurately known. We, therefore, have a calorimeter that requires no calibration. Calibration can be employed, however, by applying ohmic heating to the end of the rod. The incremental volumetric energy absorption, $d\dot{q}_o$ will be zero, but $\dot{q}_o$ will be equal to the applied energy. The use of equation (1) will corroborate the factor $\frac{kA}{L}\ \Delta T$ with the applied energy.

Using the dimensions $L = L^1 = 1.9$ cm, $A^1 = 0.713\ \text{cm}^2$ and $A = 0.0793\ \text{cm}^2$, the above calorimeter would have a $(T_1 - T_2)$ temperature difference of 10°C in a 10^8R/hr gamma field. This is using a density of 2.72 gram cm^{-3} for aluminum, a gram calorie of 4.18×10^7 ergs, 1 roentgen as 83.8 ergs per gram of air, and a stopping power of 96.5% for aluminum. The thermal conductivity of aluminum is considered to be 0.52 cal $\text{cm}^{-1}\text{sec}^{-1}{}^\circ\text{C}^{-1}$. The thermal conductivity of aluminum is reasonably constant up to 300°C.

Other materials, stainless steel, Inconel -X, tungsten, and titanium, may or may not have thermal conductivities as constant with temperature as does aluminum. If they do not, thenthe small rod may be made of aluminum and the larger part of the required material. Corrections to the equation may be made as $d\dot{q}$ for aluminum would be determined from an adjacent calorimeter.

Obviously, smaller calorimeters are required for greater radiation fields and vice versa. A shorter time constant will , therefore, be possible for measurements in higher radiation fields.

The thermocouple wires must be of small diameter because these supply a parallel conductive path, and in addition, a source of energy in a radiation field. The rod should be enclosed in an evacuated vessel to prohibit conduction and convection in the surrounding

atmosphere. This complicates the construction as vacuum seals must be employed on the thermocouple cable. Perhaps it will be sufficient to insulate with expanded polystyrene.

The base of the calorimeter must be cooled by forced gas or liquid. The highest temperature of any part of the calorimeter must remain below perhaps 200°C to limit radiation losses.

3.0 The Calorimeter Time Constant

The previous derivations and equations were based on equilibrium conditions. It is interesting to note the time constant of such a device, and it is a necessary requirement when the radiation field is not constant for a sufficiently long time for equilibrium to be established. At equilibrium, the total internal energy above that if the whole rod was at the base temperature, is

$$Q_o = aCpM\Delta T \tag{14}$$

where M is the total mass of the rod, Cp the specific heat, ΔT the measured incremental temperature, and a is a proportionality constant. The proportionality constant, a, may be computed from the geometry, and merely states that at equilibrium, the temperature distribution is fixed and is known. The factor, a, therefore relates the average temperature or internal energy, to the measured incremental temperature. For the previous sample calorimeter

$$a = \frac{1}{20}\left(1 + \frac{2AL}{2A_2 + A_1}\right) = 0.074 \tag{15}$$

Solving for ΔT in equation (14) and inserting into the equation

$$-\frac{dQ}{dt} = \frac{kA_1}{L_1}\Delta T \tag{16}$$

we have

$$-\frac{dQ}{dt} = \frac{kA_1}{L_1}\frac{Q_o}{aCpM} \tag{17}$$

which may be integrated to give

$$Q = Q_o \exp -\left[\frac{kA_1}{L_1 aCpM} \right] t \qquad (18)$$

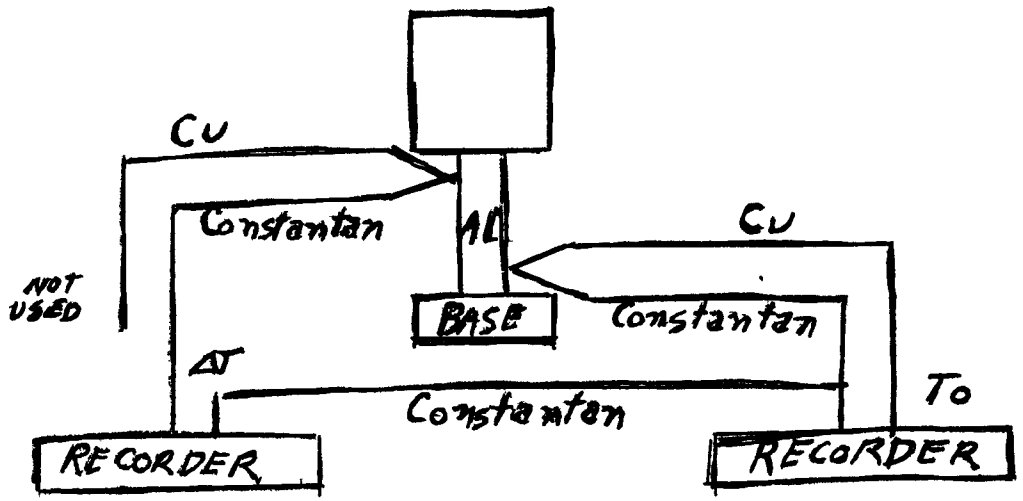
The quantity in the brackets is the time constant and has dimensions of inverse seconds, and t is the time after abrupt removal of the radiation field. The same time constant would apply for sudden insertion into a radiation field. For the sample calorimeter, a time constant of 0.0344 seconds^{-1} is computed. That is 20.1 seconds would elapse before $Q = 1/2\, Q_o$ or the total exponent equals 0.693. A total time of 7 x 20.1 = 140 seconds would be required to approach equilibrium in the sample calorimeter.

The term in the bracket is required to be large for a short response time. This requires a minimum for M, a, Cp and L_1, and a maximum for k and A_1. The smaller calorimeters will have the best response times, albeit high radiation levels will be required for a readable temperature gradient.

The projected power profile for NRX-A-2 tests evidently will not be at constant power level for long periods of time. Equilibrium may not be achieved in the calorimeters. If, however, the response times of the calorimeters are well known and the relative reactor power levels as a function of time are equally well known, the calorimeter output may be related to the actual heating rate. Analog computers could easily solve the required equations.

4.0 Recording

The temperatures T_1 and T_2 may be obtained by two separate thermocouples or the temperature difference may be recorded directly by the constantan-aluminum-constantan junctions in the rod. The below drawing indicates the required instrumentation.



Calorimeter Connections

For a temperature difference of 10°C, the constantan-aluminum-constantan junctions would deliver about 0.38 millivolts. If data handling channels are at a premium, this single channel for each calorimeter would suffice if sufficient cooling is supplied to the base such that this temperature does not vary.

The range of the ΔT measurements would be from 1°C to 100°C, or two decades. Accuracy at the low end of this range would be limited by the recorder.